Correlation of Ground Friction Measurements to Aircraft Braking Friction Calculated from Flight Data Recorders

Dr. Zoltan Radó, Dr. James C. Wambold

1 Pennsylvania State University – Pennsylvania Transportation Institute, State College, USA

2 CDRM Inc., State College, USA

ABSTRACT

Past experience and research clearly demonstrate that a contaminated runway can degrade safety to the point that takeoff and landing can become hazardous. For many years the international aviation community has had no uniform runway fiction reporting practices. The equipment used and procedures followed in taking friction measurements varies from country to country. Friction readings at various airports are made with different ground friction measurement equipment and followed practices may not be comparable. The operational characteristics of the available and used ground friction measurement devices are very different from the aircraft wheel-brake-anti-skid systems that generate the braking friction during ground maneuvers like landing or rejected take-offs for passenger aircrafts. The dual problem of the many different ground friction measurement devices in use with widely varying procedures and the fundamental difference between the operational characteristics of all the used friction devices and the aircraft braking process produces the universal problem of meaningful, safe and universal friction reporting on winter runways.

The complexity of these problems warrant a two stage investigation approach constituting a statistical approach to harmonize friction measurement results and a physical model based on aircraft landing and braking dynamics to relate the normalized measurement results to establish meaningful relationship to aircraft braking performance. A general harmonization technique was developed and evaluated for ground friction measurement equipment based on the very extensive JWRFMP database. The harmonized values called the International Runway Friction Index (IRFI) and the corresponding mathematical procedures were developed based upon a comparative statistical processing of data from a reference friction measurement device to other ground friction devices. In this paper the development and analysis of the physical model to determine braking effective friction of passenger aircraft was based on flight data recorder information collected during in-service commercial flights landing on winter contaminated surfaces. Ground friction measurements were taken after each landing to provide data to compare the aircraft friction to those measured by the friction measurement equipment. Results indicate that in addition of the possibility to predict aircraft maximum braking efficiency on winter contaminated runways with ground friction equipment, the harmonization and normalization of such predictions across different measurement techniques is feasible.

1 INTRODUCTION

In spite of advances in aviation technology, operational procedures and weather forecasting, safe winter runway operations remain a challenge for airport operators, air traffic controllers, airlines and pilots who must coordinate their efforts under rapidly-changing weather conditions. Complicating the winter weather picture is the fact that criteria for safe operations on a given runway snow/wetness condition differ between airports and countries. An obvious step in the solution of ground handling accidents is to harmonize and standardize ground friction measuring vehicle values to each other and then relate the harmonized value to aircraft braking. These values can then be used in calculating aircraft stopping distance and providing to the pilot with uniform and reliable runway condition information that is independent of the airport, country or type of measuring device.

1.1 THE JOINT WINTER RUNWAY FRICTION PROGRAM (JWRFMP)

The National Aeronautics and Space Administration (NASA), Transport Canada (TC) and the Federal Aviation Administration (FAA) support the goal of reducing the fatal aircraft accident rate by 80 percent in 10 years and by 90 percent in 25 years. To help accomplish this, NASA entered into a partnership with TC and the FAA in 1996 in a 10-year winter runway friction measurement program. Hand in hand with this effort, other government agencies such as the Canadian National Research Council (NRC); the Canadian Department of National Defense (DND); the French Societé Technique des Base Aerienne (STBA); the Norwegian Civil Aviation Administration (AVINOR); the Oslo, Prague, and Munich Airports; Erding Air Force Base near Munich; and New Chitose Airport shared cost, expertise and facilities to achieve program objectives in a timely and acceptable manner with industry's guidance and support. The Joint Winter Runway Friction Measurement Program (JWRFMP) was thus formed to provide better tools for airport operators to use and more accurate and reliable runway friction data for pilots to make "go/no go" decisions for takeoff and landing during operations in adverse weather conditions.

One objective of the JWRFMP includes harmonizing friction measurements obtained with a variety of ground test vehicles on a wide range of winter runway conditions. Thus far, 19 different makes of ground test devices (47 vehicles in total) have participated. To ensure the harmonization of these different friction-measuring devices, the ASTM E17 Committee has developed a standard; E2100, titled the International Runway Friction Index (IRFI), and a committee task group will specify an acceptable reference calibration tester to ensure consistent and accurate reporting of the IRFI.

Accurately relating these harmonized vehicle friction measurements to aircraft braking performance is also a goal of this program. To achieve this objective, a variety of instrumented test aircraft have been involved since the start of this program in January 1996. During the course of conducting the aircraft test runs, a determination has been made that the IRFI does relate directly to aircraft braking performance and that contaminant drag is a significant factor in aircraft takeoff performance.

The main objective of the last tests run at the New Chitose airport in Japan during the winter of 2003 was to determine the braking friction value of airplanes such as B767, B777 or other wide-body aircraft during landing and compare it with data measured after each landing with the different ground friction measurement devices. A most important priority of the study was to use actual in service passenger flights to obtain aircraft braking performance data. To achieve the this objective, the data recorded in the Quick Access Recorder (QAR) or other digital Flight Data Recorder (FDR) or management systems from the selected aircrafts were collected and analyzed and the aircraft braking friction was calculated.

According to the test design, after each selected wide-body airplane landing, the ERD (Electronic Recorder Decelerometer), IRV (International Reference Vehicle) and the airport's Ground Friction Measuring Device (GFMD) were to make a measurement run and report the friction of index of each particular device which in turn was to be used to calculate and report the International Runway Friction Index (IRFI) according to the ASTM E2100 standard. The reported IRFI and the calculated aircraft braking friction were to be compared to evaluate the agreement between the IRFI index and the actual effective aircraft braking coefficient.

1.2 SCOPE AND ACCOMPLISHMENTS

NASA and TC are leading this study with support from the NRC, FAA, AVINOR, and STBA. Also participating by providing aircraft and ground vehicles are organizations and equipment manufacturers from North America, France, Norway, Sweden, Scotland, Germany, Czech Republic, Japan, and the United Kingdom. A variety of instrumented test aircraft and ground friction measuring vehicles have been used at different test sites in the U.S., Canada, Norway, Germany, Czech Republic, and Japan. Data obtained during these investigations helped define the methodology for an International Runway Friction Index (IRFI) to harmonize the friction measurements obtained with the different ground test vehicles. Testing has been conducted at the following Airports:

- Jack Garland Airport, North Bay, ON
- Ottar K. Kollerud Test Track, Gardermoen Airport, Oslo, Norway.
- Sawyer Airbase, Gwinn, MI.
- Franz Josef Strauss Airport, Munich, Germany
- Erding Air Force Base, Erding, Germany
- Ruzyne Airport, Prague, Czech Republic
- New Chitose Airport, Sapporo, Japan
- Wallops flight Facility, VA
- LCPC test track, Nantes, France

2 CORRELATION OF GROUND FRICTION MEASUREMENTS TO INSTRUMENTED TEST AIRCRAFT BRAKING

Eleven weeks of NASA Aircraft Tire/Runway Friction Workshop data (1994-2004) have been combined with data from twenty-one weeks of winter testing at North Bay, ON (1996-2003), one week at Sawyer Airbase, Gwinn, MI (1999), and two weeks at Oslo, Norway (1998-99), one week at Munich Airport, Germany (2000), one week at the Airbase at Erding, Germany (2001), one week at the Prague Airport (2002), and one week at the New Chitose Airport (2003), Figure 1 is bar chart showing the data collected each year since 1996 indicating total number of test runs and segments (100 m) conducted at all test sites.

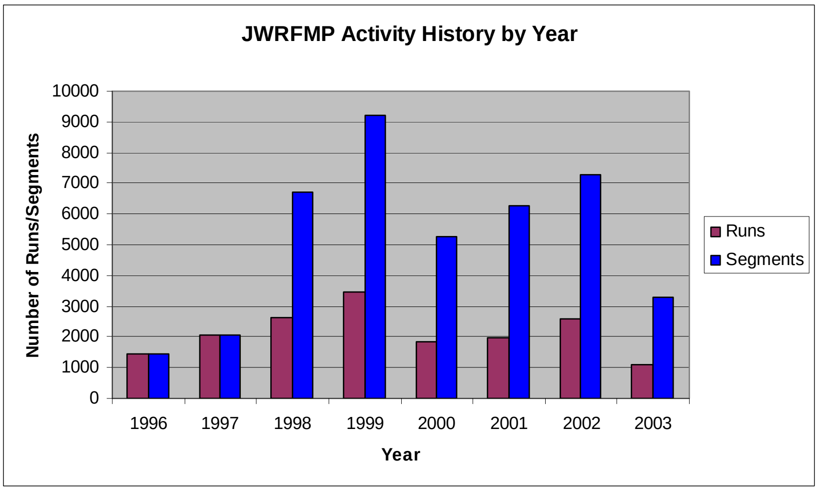

Figure 1. Number of runs and segments runs made by year

Since the beginning of the Joint Winter Runway Friction Measurement Program in January 1996, ten (10) aircraft and forty-seven (47) different ground devices collected friction data at North Bay, Ontario, Sawyer Airbase, Gwinn, MI, NASA Wallops Flight Facility, VA, Oslo, Norway, Munich, and Erding Germany, Prague, Czech Republic, and Sapporo, Japan. A total of 442 aircraft runs and over to 16,000 ground vehicle runs were conducted on nearly 50 different runway conditions. Over 400 individuals from nearly 60 organizations in 16 different countries have participated with personnel, equipment, facilities and data reduction/analysis techniques. The Canadian Runway Friction Index (CRFI) and the International Runway Friction Index (IRFI) are the major outcomes from these efforts to harmonize ground vehicle friction measurements to aircraft stopping performance. Three international aviation conferences have been held in Montreal (Oct. 1996, Nov. 1999 and Nov. 2004) to disseminate the test results and obtain recommendations for future testing.

Figure 2 shows the present correlation between aircraft effective braking friction and the IRFI for five different aircraft. Some of this aircraft data is preliminary, but a single correlation of IRFI is possible with the different aircraft tested. The aircraft effective braking friction coefficient values were obtained from test runs with the NASA B737 and B757, the FAA B727, the NRC Falcon 20 and the manufacturer's Dash 8 aircraft under a variety of snow- and ice-covered runway surface conditions. The IRFI values were derived from both the IMAG trailer (15% slip) and the Electronic Recording Decelerometer data measured before and after each aircraft test series. The ambient temperature variation was within 10 degrees Celsius. Table 1 gives a summary of IRFI correlations for each device, the tire type, the linear correlation coefficients and the standard errors using the ground vehicle data through 1999. Additional analysis of the data collected since 1999 shows a similar correlation, and standard errors.

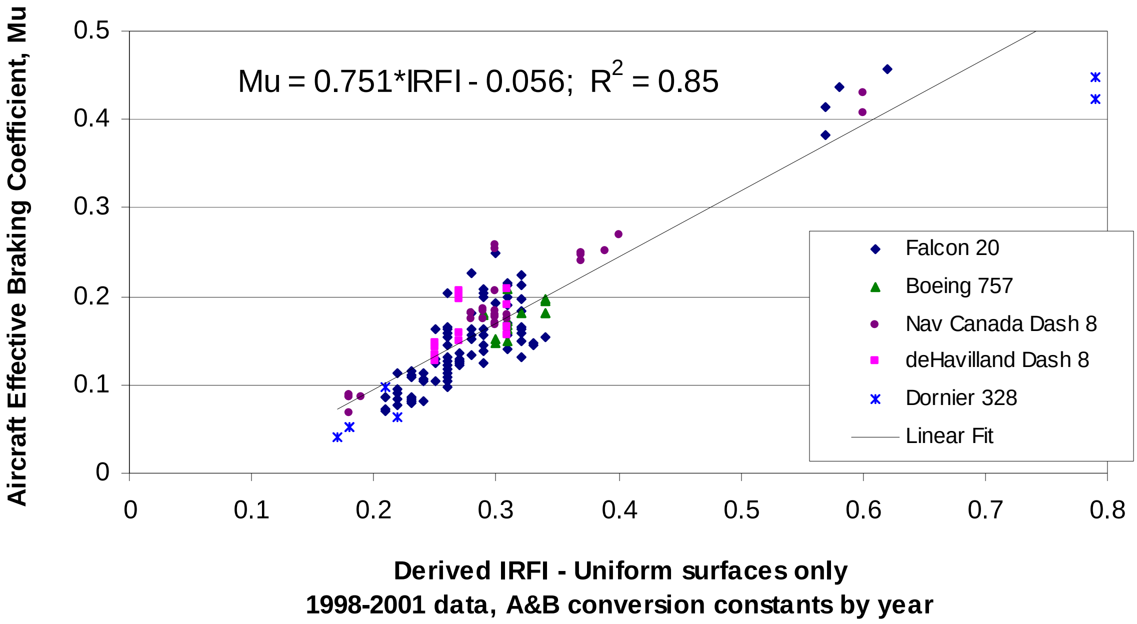

Figure 2. Correlation between test aircraft effective braking friction and IRFI.

Table 1. Harmonization of Ground Vehicle Friction Measurements

Device Description	Tire Type	Correlation Coefficient R^2	Standard Error of Estimate
Airport Surface Friction tester SAAB 95*	Trelleborg AERO 890 kPa (100 psi)	0.78	0.023
FAA Trailer BV-11	Trelleborg T520 690 kPa (100 psi)	0.83	0.052
TC ERD in Chevrolet 1500 Truck		0.73	0.045
DND Grip Tester	ASTM E-1844	0.82	0.042
NASA Instrumented Tire Test Vehicle	Aircraft Tire 26 by 6 inches	0.92	0.048
FAA Runway Friction Tester**	ASTM E-1551 69 kPa (100 psi)	0.98	0.034
Norsemeter RUNAR	ASTM E-1551 207 kPa (30 psi)	0.77	0.030
TC Surface Friction Tester SAAB 1979	ASTM E-1551 69 kPa (100 psi)	0.92	0.034
Munich Airport Surface Friction Tester	Trelleborg AERO 69D kPa (100 psi)	0.67	0.044

*1998 data only
**Small number of data points

2.1.1 Friction Database

A substantial friction database has been established, with both ground vehicle and aircraft friction measurements. For each friction value, the database provides the name/type of device, test location, speed, tire specifications, surface conditions and ambient weather conditions. Table 2 is a list of all of the ground friction devices that have participated in the JWRFMP. Figure 3 is a photo of the Falcon 20 performing a test run and Table 3 is a list of all of the aircraft that have run tests in the JWRFMP.

Table 2. List of Ground Test Devices

Owner	Device Name	Notes	Manufacturer
Airport Surface Friction Tester AB, Sweden	Airport Surface friction Tester Ford Taurus		Airport Surface Friction Tester AB, Sweden
Airport Surface Friction Tester AB, Sweden	Airport Surface Friction Tester Generic		Airport Surface Friction Tester AB, Sweden
Oslo Airport, Norway	Airport Surface Friction Tester SAAB 9-5		Airport Surface Friction Tester AB, Sweden
Airport Surface Friction Tester AB, Sweden	Airport Surface Friction Tester SAAB 9-5C		Airport Surface Friction Tester AB, Sweden
NASA Langley Research Center	BOWMONK mounted in Blazer		Bowmonk, United Kingdom
FAA Technical Center	BV-11 Trailer		Airport Equipment Company, Sweden
Oslo Airport, Norway	BV-11 Trailer		Airport Equipment Company, Sweden
Vienna Airport, Austria	BV-11 Trailer Vienna Airport		Airport Equipment Company, Sweden
Zurich Airport, Switzerland	BV-11 Trailer Zurich Airport		Airport Equipment Company, Sweden
NASA Langley Research Center	Diagonal Braked Vehicle		NASA Langley Research Center, USA
Transport Canada	ERD mounted in Chevrolet Blazer		Transport Canada, Canada
Transport Canada	ERD mounted in NISSAN Van		Transport Canada, Canada
Transport Canada	ERD mounted in truck Staff23, North Bay		Transport Canada, Canada
Transport Canada	ERD-179 mounted in Chevrolet Blazer		Transport Canada, Canada
Transport Canada	ERD-234 mounted in Chevrolet Blazer		Transport Canada, Canada
Irvine Findley Inc., Scotland	Griptester Trailer		Findley Irvine Inc., Scotland
Dept. of National Defense, Canada	Griptester Trailer		Findley Irvine Inc., Scotland
Norwegian Air Traffic and Airport Management.	Griptester Trailer		Findley Irvine Inc., Scotland
French Civil Aviation Administration	IMAG Trailer		S. T. B. A. Airports, France
NASA Langley Research Center	Instrumented Tire Test Vehicle		NASA Langley Research Center, USA
NASA Langley Research Center	Griptester Trailer		Findley Irvine Inc., Scotland
Tyndall AFB	Griptester Trailer		Findley Irvine Inc., Scotland
French Civil Aviation Administration	IRFI Reference Vehicle Trailer		S. T. B. A. Airports, France
Ministry of Transportation, Ontario	Norsemeter ROAR Trailer		Norsemeter AS, Norway

Department of Transportation, Iowa	Norsemeter SALTAR		Norsemeter AS, Norway
Norwegian Road Research Laboratory, Oslo	Optimum Surface Chart Analyzer Recorder		Norsemeter AS, Norway
Norwegian Air Traffic and Airport Management	RUNAR Prototype Trailer		Norsemeter AS, Norway
FAA Technical Center	Runway Friction Tester		K. J. Law Engineers, Inc., USA
Frankfurt Airport, Germany	Safegate SAAB 9-5 Mrk APT5, Ser #527		Safegate, Sweden
Munich Airport, Germany	SARSYS SAAB 9000 Mrk V3		SARSYS, Sweden
Dusseldorf Airport, Germany	SARSYS SAAB 9-5C, Ser #813		SARSYS, Sweden
Strata Contractor, Germany	SARSYS SAAB 9-5C, Ser #814		SARSYS, Sweden
FAA Technical Center	Surface Friction Tester		SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1979		SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1985		SAAB GM, Sweden
Transport Canada	Surface Friction Tester SAAB 1985, Turbo		SAAB GM, Sweden
Hannover Airport, Germany	Surface Friction Tester		SARSYS, Sweden
NASA Langley Research Center	Tapley meter mounted n Blazer		Tapley, Canada
Pennsylvania State University	ASTM E-274 2 Wheel Trailer	Wallops Only	Pennsylvania State University, USA
Pennsylvania State University	ASTM E-274 trailer Mk III	Wallops Only	Pennsylvania State University, USA
Department of Transportation, Virginia	ASTM E-274 Trailer	Wallops Only	International Cybernetics, USA
Department of Transportation, Virginia	British Pendulum Tester	Wallops Only	W. F. Stanley, United Kingdom
Federal Highway Administration	British Pendulum Tester	Wallops Only	W. F. Stanley, United Kingdom
Pennsylvania State University	British Pendulum Tester	Wallops Only	W. F. Stanley, United Kingdom
Nippo Sangyo Co., Ltd.	British Pendulum Tester	Wallops Only	Nippo Sangyo Co., Ltd., Japan
Generic device	Mu-Meter Trailer	Wallops Only	Douglas Equipment Co., United Kingdom

Figure 3. Photograph of Falcon-20 aircraft during test run on snow-covered runway.

Table 3. List of instrumented test aircraft

AIRCRAFT TYPE	OWNER/OPERATOR	MANUFACTURER
Falcon-20	National Research Council of Canada	Dassault Aircraft Company
B-737-100	NASA Langley Research Center	Boeing Commercial Airplane Group
B-727-100	FAA Technical Center	Boeing Commercial Airplane Group
Dash-8	DeHavilland Aircraft Company	DeHavilland Aircraft Company
Dash-8	NAV CAN	DeHavilland Aircraft Company
B757-200	NASA Langley Research Center	Boeing Commercial Airplane Group
A320	Aero Lloyd	Airbus Industrie
A320	Sabena Airline	Airbus Industrie
B-737-300	Deutsche British Airways	Boeing Commercial Airplane Group
DU 325	Donier	Fairchild/Donier

At all test sites, NRC provided an ice and snow tribology researcher who classified the winter contaminate. Typically, the water content, density, temperature of air, contaminant and pavement, and the depth of the contaminate was measured and observations were recorded on the tire tracks produced during aircraft and ground vehicle test runs. This data along with the hourly flight weather is included in the database. Similarly, NASA and/or TC provided still photographs and videos of all the testing and surfaces.

3 DEVELOPMENT OF PHYSICAL MODEL FOR COMMERCIAL FLIGHTS

During a landing aircrafts use their speed brakes, spoilers, flaps and hydraulic and mechanic braking systems and other means to decelerate the aircraft to acceptable ground taxi speed. The performance of these systems together with many physical parameters including various speeds, deceleration, temperatures, pressures, winds and other physical parameters are monitored, measured, collected and stored in a data management system on board of most wide-body aircrafts (see Figure 4).

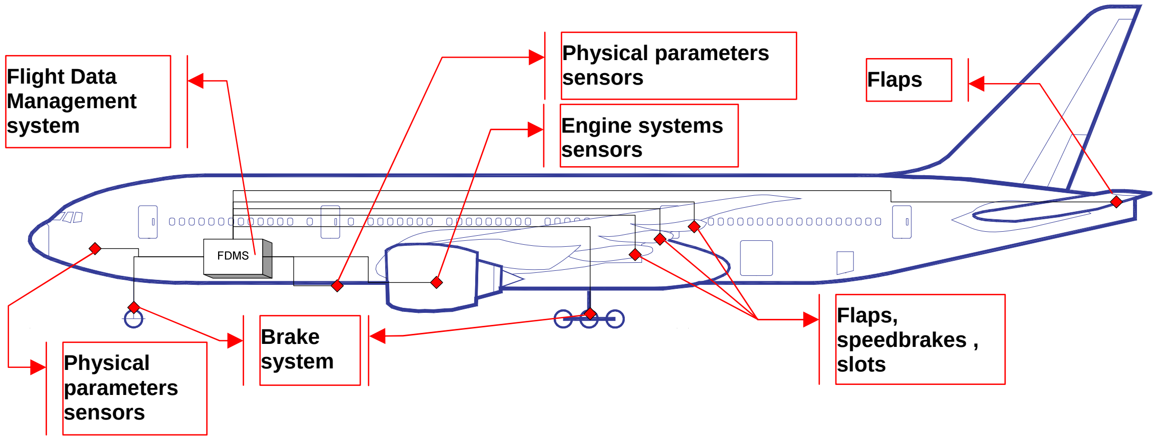

Figure 4. Flight Data Recorder schematic

All monitored parameters can be collected from the flight data management system and fed into a high power computer system which is capable of processing the data and calculating all relevant physical processes involved in the aircraft landing maneuver. Based upon the calculated physical processes the actual affective braking friction coefficient of the landing aircraft can be calculated. This together with other parameters and weather data can be used to calculate the true aircraft landing performance parameters.

Using the recorded data stream of the aircraft including the actual settings of speed brakes, flaps, spoilers, fuel flow, engine rpm, trust reversal setting of the engine, aircraft landing weight, plus the recorded environmental factors including the wind speed barometric pressure, temperature, humidity, dew point and knowing specific performance and design parameters of the aircraft including the geometric design (length , width, wing span, number of wheels, lift and aerodynamic lift and drag coefficients for different air-control device settings) a dynamic simulation was developed to calculate all relevant actual retarding forces acting on the aircraft as the function of the true ground and air speeds, travel distance and time. Together with these and the known parameters of aircraft landing weight the dynamic wheel loads of all main gears and the nose gear can be simulated.

Knowing the full retardation of the aircraft measured by the onboard systems, the deduction of the calculated retardation forces by means of known aircraft mass together with the measured gravitational biases by aircraft physics can be completed. This calculation yields the true retardation actually inflicted by the aircraft main gear's braking system. Knowing this braking retardation force together with the aircraft landing weight and the calculated dynamic lifting forces the actual effective generated braking friction force and consequently the necessary braking torque can be deducted. Using the calculated effective true frictional forces together with parameters measured by the aircraft data management system such as downstream hydraulic braking pressure a logical algorithm based on the physics of the braking of pneumatic tires with antiskid braking systems is designed to determine if the maximum available runway friction was reached during relevant speed ranges of the landing maneuver. Together with the actual friction force this logic was used to determine:

(A) In case friction limited braking is encountered, the actual available maximum braking friction available for the aircraft is calculated.

(B) In case friction limited braking was not generated and the braking was limited by the preset level of the auto-brake system, the actual friction coefficient is determined. The obtained friction coefficient then is compared to the level set by the auto-brake setting to verify if adequate if for the pre-set brake setting adequate friction was available.

4 TEST DATA COLLECTION

Two types of landing configurations and procedures for aircrafts were designed and prepared in the test plan. One is to ensure the configuration and pilot procedure of the landing aircraft produces data recorded in the aircraft QAR that enables the calculation of the aircraft braking friction during normal landing; these were called braking runs. The other is to ensure the configuration and pilot procedure of the landing aircraft produces data recorded in the aircraft QAR that enables the precise calculation of:

1. The effect of the spoilers (speed brakes), ailerons, flaps and aircraft body,
2. The effect of the thrust-reversal.
3. The effects of the wheel drag (rolling resistance).

These aircraft landings were called TARE runs.

4.1 TARE RUNS

The objective of these landings was to generate flight recorder data that allows deducting aircraft parameters not otherwise known. The recommended pilot procedures together with the utilized aircraft configuration was designed to ensure that special and clear QAR data with two distinct time windows is produced during the landings. The first time window was to create a sufficiently long time trace of aircraft parameters with no braking and no thrust-reversal applied. The other time window was to ensure that all the collected aircraft parameters are available for a minimum time trace with normal flap configuration and thrust reverser setting but no braking.

To obtain the above goals and generate the necessary QAR data the following procedure was recommended for the pilots.

1. After the nose gear touches the ground and before the braking starts, the aircraft should coast with no brake and no thrust-reversal for 4-5 seconds.
2. After the initial 4-5 second coasting the thrust-reverser should be turned on, but no brake applied and the aircraft should coast for another 4-5 seconds.
3. After that the normal braking procedure should be applied.

4.2 BRAKING RUNS

The braking runs were essentially normal aircraft landings that took place on winter contaminated surfaces under normal airport operations. One aim of the study was to observe aircraft landing operations under normal airport operations and collect the data only on those winter contaminated surfaces that occur under normal winter operations. The objectives of these landings were to generate the time traces of all aircraft parameters in the flight data recorder where friction limited braking sections were achieved. This can only be obtained with as high as possible auto-brake settings.

To obtain the above the following procedure was proposed for the pilots:

1. After the nose gear touches the ground and before the braking starts, the aircraft should coast with no brake and no thrust-reversal for 1-2 seconds.
2. After the steady-state coasting the thrust-reversal should be turned on, but no brake applied and the aircraft should coast for another 1-2 seconds.
3. When the stabilized base line thrust reverser deceleration is achieved the normal landing procedure should be applied with as high as possible auto-brake settings.
4. After reaching the taxi-speed the aircraft should coast for 1-2 seconds with no brake and no thrust-reversal if it is possible to provide control data.

With this procedure the standard landing practice was followed, with as little deviation from it as possible. After touch down first the thrust reversal, then the brake was switched on and after reaching the appropriate low speed the thrust reversal was switched off and when the airplane reached the taxi speed the brake was switched off. The only change request was that the pilots delay switching on the trust-reversal and the brake based on best judgment, possibly with 1-2 seconds each. At the end of the landing maneuvers when the normal taxi speed was reached a short second coasting (no thrust, no thrust reversal, and no brakes) for 1-2 seconds was inserted before proceeding with normal taxiing.

4.3 ANALYSIS OF PHYSICAL MODEL

A total of 43 flights have been identified as candidate to be included in the study where the requested procedures were followed on winter surfaces. The flights data recorded in the QAR systems were saved and paired with the additional airport data for future analysis. The data validation, checking of actual runway conditions, the inspection of the ground friction measurement data and other consistency assessment has eliminated a number of landing data sets. After the inadequate datasets were eliminated the following flights had been included in aircraft braking friction runs analysis. The selected flights are shown in Table 4. The actual flight numbers and precise times have been removed from the tale to prevent positive identification of the flights.

Table 4. Aircraft braking friction runs

Data File	Landing Date	AC
S9.txt	JAN20_2003	B767-300
S4.txt	JAN20_2003	B767-300
S5.txt	JAN21_2003	B767-300
S6.txt	JAN22_2003	B767-300
S2.txt	JAN22_2003	B767-300
S12.txt	JAN23_2003	B767-300
S17.txt	JAN23_2003	B767-300
S10.txt	JAN24_2003	B767-300
S8.txt	JAN24_2003	B767-300

S3.txt	JAN24_2003	B767-300
S7.txt	JAN29_2003	B767-300
S1.txt	JAN29_2003	B767-300
S13.txt	JAN29_2003	B767-300
S15.txt	JAN29_2003	B767-300
S11.txt	JAN30_2003	B767-300
S14.txt	JAN30_2003	B767-300
S16.txt	JAN31_2003	B767-300

The tare runs to determine physical parameters of the aircraft otherwise not known or not obtainable by the group of scientists involved in the tests were performed later in 2003 when the weather conditions together with runway surface conditions allowed the safe exercise of the particular requirements of landing procedures that were necessary. For the study a total of four tare runs were completed during the test. (see Table 5)

Table 5. Tare runs

Data File	Landing Date	AC
T1.txt	MAR09_2003	B767-300
T2.txt	MAR09_2003	B767-300
T3.txt	MAR10_2003	B767-300
T4.txt	MAR13_2003	B767-300

Additionally the QAR data, for each landing, the Flight Operation – Engineering – and the Airline provided the following datasheets:

1. SNOWTAM
2. Weight and balance manifest
3. METAR

From these data sheets the data has been collected and used in the data analysis. The compiled data is shown in Table 6.

Table 6. Additional data

Data File	Landing Weight (Aircraft data) (lsb/kg)	Reported Landing weight (lbs/kg)	Air T °C	Pressure Altitude ft	Air Pressure (kPa/in Hg)	Rel. hum. (%)	SAAB Friction Measurement
T1.txt	254720/114624	Not Reported	-8	150	101.30/29.92	86	Not Reported
T2.txt	248960/112032	Not Reported	8	-160	101.30/29.92	88	Not Reported
T3.txt	241920/108864	Not Reported	21	-260	100.60/29.71	94	Not Reported
T4.txt	234880/105696	Not Reported	4	-300	99.80/29.47	90	Not Reported
S1.txt	234880/105696	238700/107415	-4	780	99.60/29.41	95	34/35/35

S2.txt	241920/108864	242800/109260	-1	300	101.30/29.92	75	95/95/95
S3.txt	245120/110304	245800/110610	-1	288	100.70/29.75	100	33/32/35
S4.txt	235520/105984	235200/105840	-2	450	100.80/29.78	90	95/95/95
S5.txt	227840/102528	231000/103950	-4	330	101.20/29.90	92	95/95/95
S6.txt	237440/106848	239900/107955	-2	310	101.40/29.95	90	95/95/95
S7.txt	235520/105984	236100/106245	-4	810	99.50/29.40	95	28/29/29
S8.txt	255680/115056	255800/115110	-1	430	100.85/29.79	80	95/95/95
S9.txt	230080/103536	230500/103725	-3	420	100.90/29.81	75	95/95/95
S10.txt	230720/103824	232900/104805	0.5	595	100.40/29.64	88	95/32/27
S11.txt	238720/107424	240500/108225	-3	380	101.10/29.85	100	27/29/27
S12.txt	247680/111456	249600/112320	0	720	99.80/29.47	100	26/26/26
S13.txt	245760/110592	247400/111330	-5	720	99.90/29.49	100	34/26/39
S14.txt	239360/107712	240000/108000	2.5	270	101.50/29.97	80	39/36/34
S15.txt	248960/112032	253400/114030	-5	685	99.90/29.49	100	35/35/35
S16.txt	242560/109152	243300/109485	-4	225	101.60/30.02	86	95/31/29
S17.txt	238720/107424	242100/108945	0	750	99.75/29.46	100	24/24/24

The four tare data sets were utilized in the first step to calculate and produce the unknown physical parameters for the aircrafts used in this test. These parameters included the aerodynamic drug coefficient, modified dynamic aerodynamic lift coefficient, the dynamic retarding force as a function of engine parameters and others. The dynamic simulation software then was equipped with these missing parameters and the processing of each selected data set with the dynamic simulation was complete. For each landing the simulation software produced four graphs:

1. Measured acceleration and Brake effective acceleration vs. time.
2. Measured ground speed and Integrated ground speed and Ground/Air speed vs. time
3. Main wheel load and brake pressure and wheel friction vs. time
4. Pressure vs Mu correlation

A sample of the simulation outputs is shown on Figure 5.

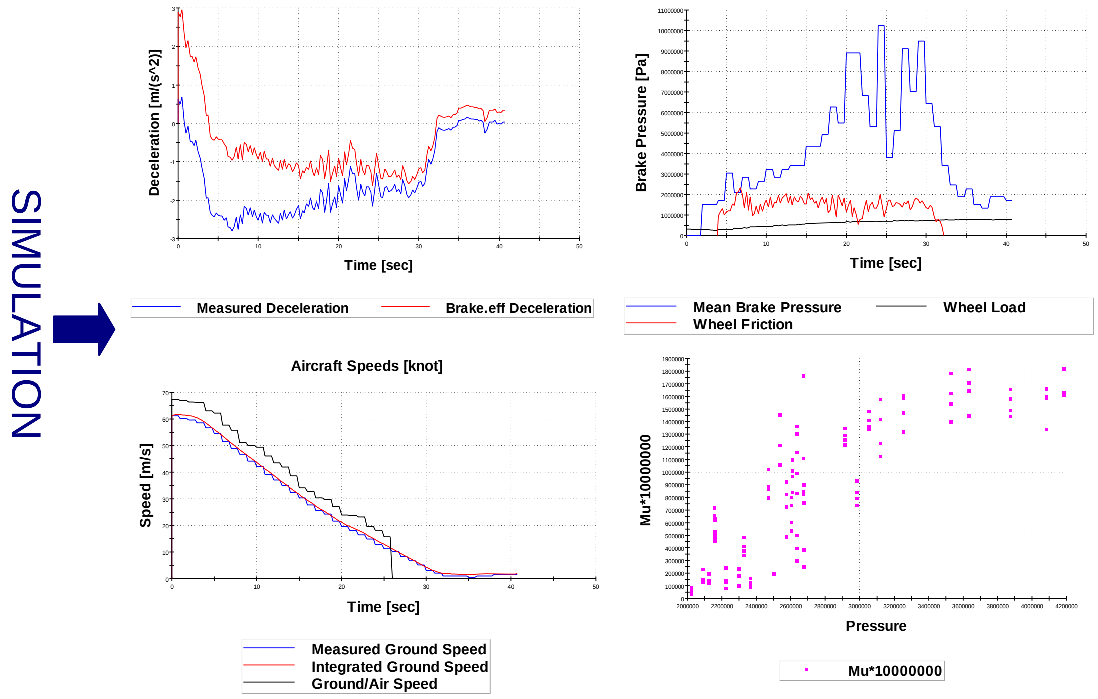

Figure 5. Sample simulation output in graphical format

For each of the selected landing data sets the data for the graphs together with additional time and distance traces were produced. Some of the produced data was generated by the simulation to cross check the validity of the model and of the aircraft input data traces. These additional data and figures are not discussed in this paper. Based on these graphs, the friction limited runs have been identified. The identification process was programmed into the simulation method by means of mathematical analysis. The different mathematical techniques employed were programmed using the following logical method.

1. For each landing the time window was defined where the landing speed was between 60 m/s and 20 m/s. In order to make sure that the auto-brake and antiskid systems of the aircraft were working in their operational range the algorithm analyzed the data to look for the friction limited sections only in this time window.
2. Within the speed validated time window the main brake pressure and the wheel friction was compared and where the wheel friction could not follow the increasing brake pressure was identified as the friction limited section. The time window for the friction limited section has also been identified and recorded.
3. The identified friction limited sections were verified using the effective braking friction and pressure data. If the segmented pressure-friction graph has vertical or declining sections that match the identified friction limited sections then the braking was friction limited.

The above described procedure is graphically illustrated on Figure 6, Figure 7, and Figure 8 and can be easily followed using the figures as guides. On Figure 6 the selection of the time window for a particular data set is demonstrated based upon the speed limit criteria.

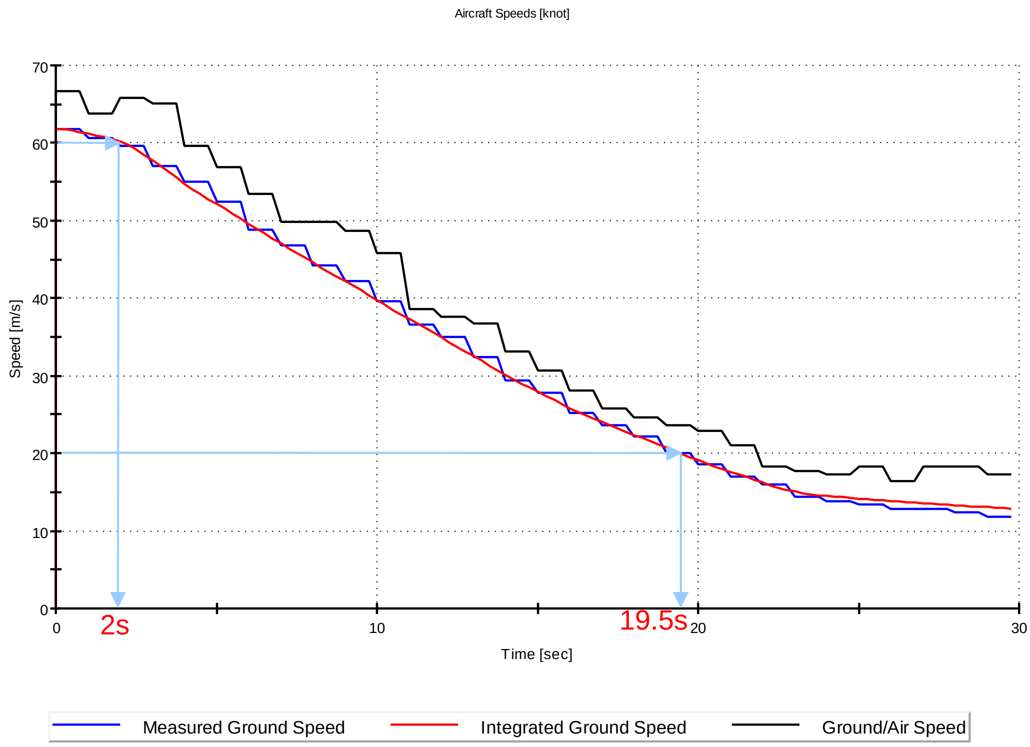

Figure 6 Definition of speed limited time window

The data within the determined time window then is analyzed for the deviation of the applied downstream hydraulic brake pressure and the obtained effective braking friction as shown in Figure 7. A sharp deviation from the achieved true effective braking friction calculated by the simulation based on the dynamic model from the hydraulic pressure is the indication of friction limited braking. When sharply increased hydraulic pressure is applied by the braking system while no significant friction increase is generated the potential of true friction limited braking occurs.

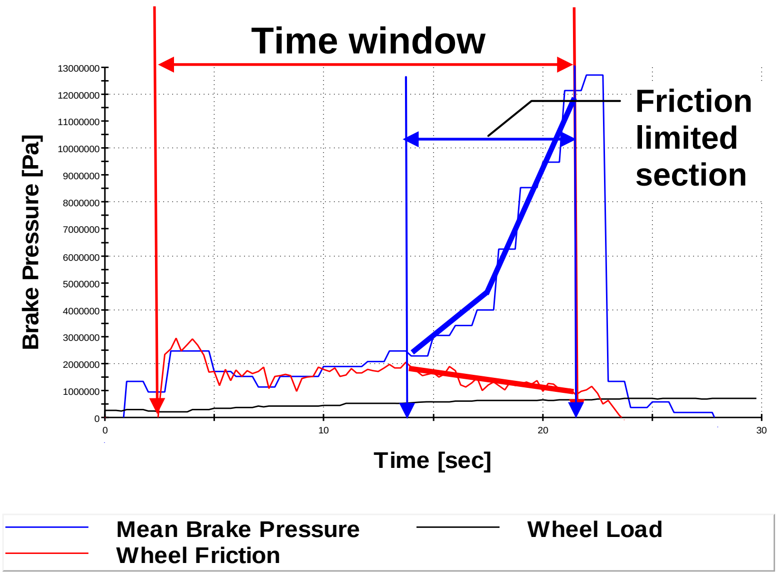

Figure 7. Definition of friction limited section

The friction and pressure data is segmented to precisely determine the actual extent of the friction limited length of the braking maneuver as well as to validate the assumption of friction limited braking.

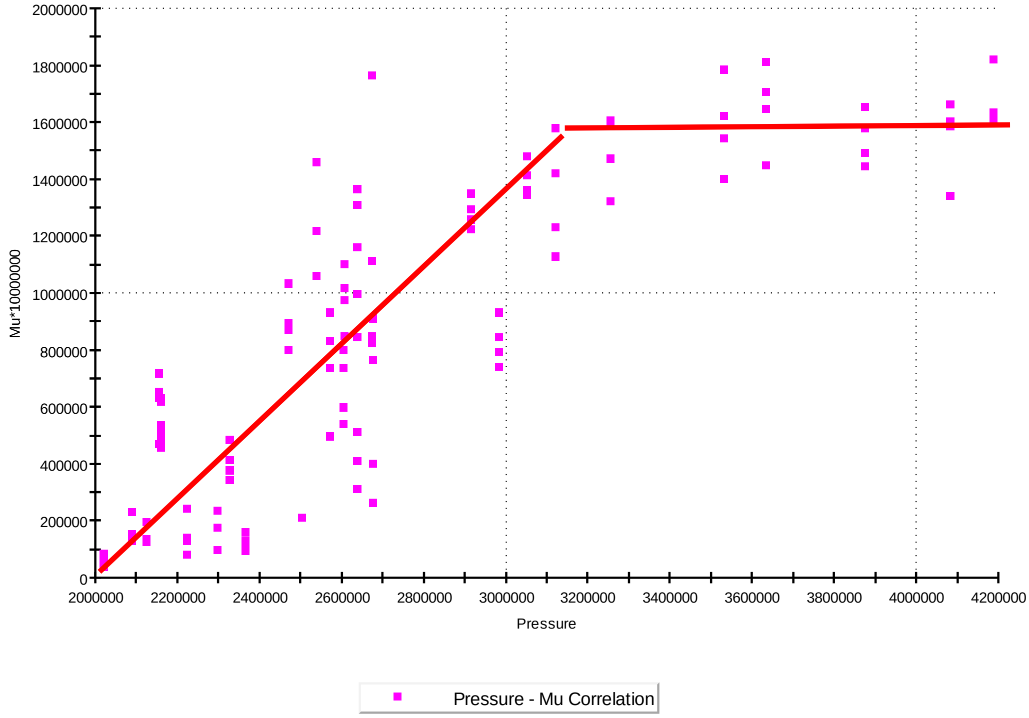

Figure 8. Segmented friction-pressure graph

For the friction limited landings identified the available average friction has been calculated by averaging the generated effective braking friction in the friction limited time window.

From the data in Table 4 the following data sets proved to produce true friction limited braking data: S3, S7, S10, S12, S13, S14, S16, and S17. The obtained final results are collected in Table 7.

File Name	Saab friction	Aircraft friction
S3.txt	0.33	0.17
S7.txt	0.29	0.14
S10.txt	0.30	0.12
S12.txt	0.26	0.08
S13.txt	0.30	0.15
S14.txt	0.36	0.21
S16.txt	0.30	0.17
S17.txt	0.24	0.07

Table 7. Compiled friction limited braking data

The obtained friction values have been compared to the measured friction by the ground friction measurement device used by the New Chitose airport which was a Saab Friction Tester. The paired data can be observed in Figure 9. The correlation of the measured ground friction to the simulation provided effective braking friction data is convincing. The obtained correlation coefficient shows a strong dependency of the aircraft braking friction on the reported ground friction measurements.

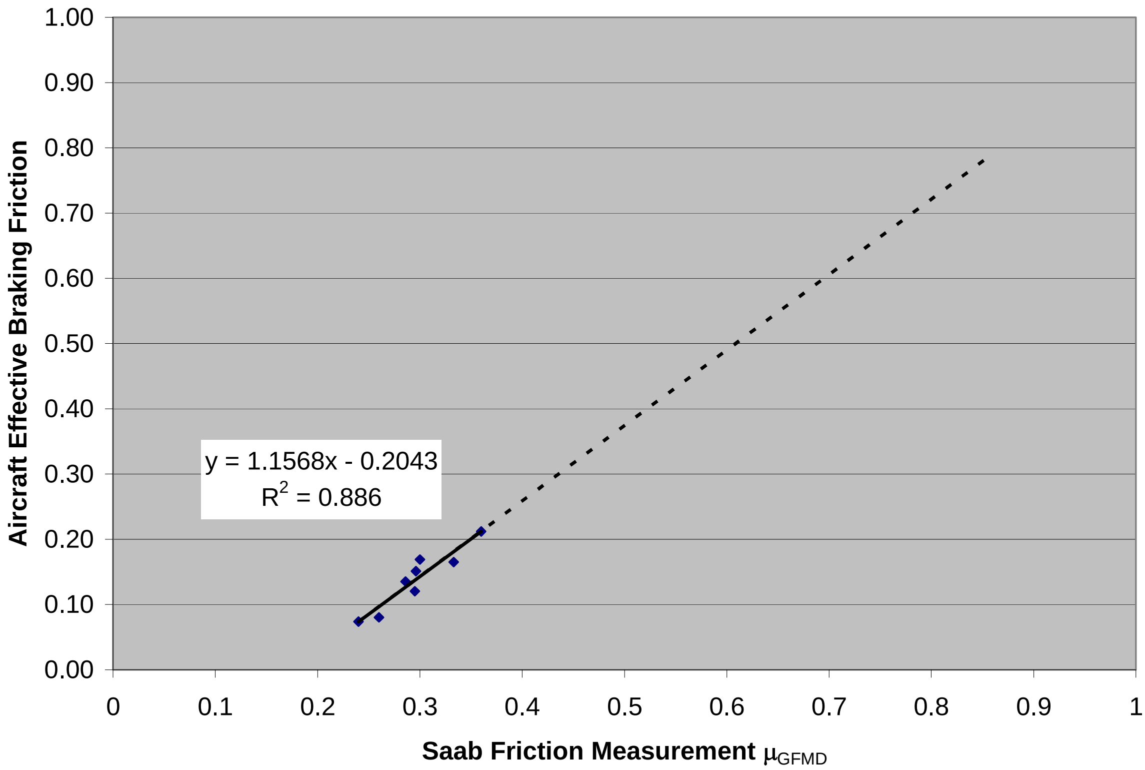

Figure 9. Correlation of calculated aircraft braking friction and ground friction measurement

5 CONCLUDING REMARKS

In the ten years of testing aircraft and ground vehicles in the joint program, a substantial friction database has been established. Both an International and a Canadian runway friction indices have been identified from ground vehicle and aircraft friction measurements. Data analysis is continuing to improve the harmonization of ground vehicle friction measurements and determine a suitable Aircraft Friction Index based on calculated aircraft stopping distances using IRFI, that pilots could use in making their "go/no go" decisions.

Additionally from the analysis of the passenger flight data and its comparison to the ground friction measurement data the following conclusions can be drawn:

- It is possible to use Flight Data Recorder information to get aircraft braking friction. From simple tare runs all necessary physical parameters can be calculated for a type of aircraft to calculate braking wheel friction. These parameters can then be used in the future for that particular aircraft type.
- If an aircraft, when landing, encounters friction limited sections of the runway during braking; the flight data management recorded data can be used to accurately calculate the true aircraft braking friction.

Collection of good aircraft data with one or more GFMDs would greatly add to the present database and allow for future tests with a reference device to insure a known and good correlation between the ground friction reference device and aircraft braking.